NPS-58AD72081A

NAVAL POSTGRADUATE SCHOOL

Monterey, California

ANNUAL PROGRESS REPORT

STUDY OF DYNAMIC RIGIDITY OF MARINE SEDIMENTS

by

R. S. Andrews and O. B. Wilson, Jr.

STUDY OF UPPER OCEAN TURBULENCE AS RELATED TO ACOUSTIC MEASUREMENTS

by

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August 1972

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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ABSTRACT

This report covers progress for the period 1 July 1971 through 30 June 1972 under Research Project RR 131-03-01, NR 083-275, Office of Naval Research, Ocean Science and Technology Branch. The report is divided into two tasks with each task summary being prepared by the principal investigators of that task. Task 1 includes a study of the dynamic rigidity, acoustic, and other engineering properties of marine sediments. Task 2 covers a study of upper ocean turbulence as related to acoustic measurements.

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TASK 1 - STUDY OF PROPERTIES OF MARINE SEDIMENTS: DYNAMIC RIGIDITY, ACOUSTICAL, AND OTHER ENGINEERING PROPERTIES

A. INTRODUCTION

This annual report provides some background information and describes the activities of the investigators and the progress made during the period 1 July 1971 to 30 June 1972 on research relating to properties of marine sediments.

The investigators for this project were O. B. Wilson, Jr., Professor of Physics, and R. S. Andrews, Assistant Professor of Oceanography. The following graduate students, all U. S. Navy officers, participated in this project: LT R. Cepek, ENS G. Engel, LT C. Martinek, LT J. Morgan. Support personnel associated with the project included K. Smith, Electronics Technician, and D. Spiel, Physicist. In addition, some support was received from the resources of the Departments of Oceanography and Physics.

B. BACKGROUND

In recent years, attention has been given to the development of improved models for prediction of the sound reflectivity characteristics of the ocean floor. Some of these models have included the effects of shear elasticity or rigidity of the sediment and the effects of the dissipative processes (Bucker, 1965; Hamilton, 1972). Experimental determinations of the shear moduli which describe both the elastic and the anelastic or dissipative properties of a variety of materials, including relatively rigid sediments, have been carried out by a number of investigators using direct, wave propagation methods (White, 1965). For very soft sediments, the propagation speed for shear waves becomes so small that the direct observation of the wave propagation effects, which enable determination of wave speed and/or the absorption coefficient, becomes very difficult at frequencies of interest in active sonar systems.

Research carried out at the Naval Postgraduate School (NPS) has explored the use of a radiation impedance method for determining the dynamic rigidity of very soft sediments. The method is an adaptation of one developed by Mason (1947) and McSkimin (1952) for observing the viscoelastic properties of polymer solutions. In this method, the dynamic loading effects of material in contact with the side walls of a cylindrical rod which is oscillating in torsion can be interpreted to obtain the complex shear modulus of the material.

A progressive series of developments and tests of this method were carried out by Hutchins (1967), Cohen (1968), and Bieda (1970). Efforts to validate the results of this approach have been made by Lasswell (1970) and Walsh (1971). These validation tests have utilized observations of the speed of propagation of interface waves of the Rayleigh type in both natural and artificial sediments as a means for calculating a shear modulus. Comparisons with the results from the torsional oscillator (hereafter called the viscoelastometer) method have been favorable but not sufficiently precise since experimental difficulties have precluded comparing the results of each method in the same sediment at nearly the same time and under the same environmental conditions. It is important to recognize that the physical and acoustic properties of a sediment deposit may be unique and that differences in the immediate past history of the deposit have strong effects on these properties.

C. SUMMARY OF OBJECTIVES AND PROGRESS

The objectives for our work during this reporting year have been to determine the validity of the oscillating torsional probe viscoelastometer method for measuring the dynamic rigidity (or complex shear modulus) of soft sediments and to study the relationships between this property and the acoustic and other engineering and mass-physical properties of recent marine sediments. These studies were to have been conducted using the existing instrument and with new and improved viscoelastometers being developed.

The activities and progress during this year may be summarized as follows. Some preliminary compressional wave absorption and speed measurements were made using a direct method in an artificial sediment, a water-saturated kaolinite clay. Some viscoelastometer measurements, made in the same sediment, show a consistency between the real part of the dynamic rigidity determined with this instrument and with other independent methods. A new and improved model of the resonance-method viscoelastometer has been designed and constructed and is now undergoing tests. Another viscoelastometer, based on a different operating principle, has been designed and is being constructed. A number of gravity core sediment samples have been collected from the Monterey Submarine Fan and engineering tests, principally vane-shear strength, and other mass-physical properties have been completed. Viscoelastometer measurements on these samples will be conducted this summer. Much of the instrumentation for in situ field experiments in shallow water estuarine muds has been assembled.

A master's thesis entitled "Compressional Wave Speed and Absorption Measurements in a Saturated Kaolinite-Water Artificial Sediment" reported much of the results of this year's work. A summary of the work done on this subject prior to the funding period, entitled "Measurement of the Dynamic Rigidity of Sediments," was presented by the investigators at the International Symposium on the Engineering Properties of Sea-Floor Soils and Their Geophysical Identification in Seattle, Washington.

There now follows a somewhat more detailed description of the viscoelastometer method, the apparatus, and some of the experiments carried out this year.

D. THEORY OF THE VISCOELASTOMETER METHOD

The torsional probe viscoelastometers used previously and one of those presently being tested depend upon sensing the changes in the frequency of mechanical resonance and in the damping factor of a torsional mechanical oscillator when the oscillator is imbedded in the sediment. The use of such a viscoelastometer has been described in detail by Mason (1947) and McSkimin (1952). This oscillator may take the form of a cylindrical piezoelectric transducer or of a transducer-rod assembly which oscillates in torsional modes. At mechanical resonance, a standing torsional wave exists along the axis of the system and the piezoelectric transducer which drives the system will have a maximum electrical conductance which depends upon the physical dimensions of the system and the properties of its constituents. Upon being immersed and making contact with a medium, shear waves are generated in the medium immediately adjacent to the system's surface and propagate radially outward. Although the shear waves in the sediment are usually too highly attenuated to allow investigation of their propagation, the radiation itself has a loading or damping effect on the system. This loading effect causes the resonant frequency and electrical conductance of the transducer to undergo a measurable change which is a function of the complex shear modulus of the medium. With properly evaluated constants of proportionality, the real and imaginary parts of the shear modulus can be determined.

Following Mason's development, if it can be assumed that the shear waves propagating radially outward into the material in contact with the surface of the rod have a wave length which is very small compared with both the radius of curvature of the rod and the shear wave length in the rod and that the amplitude of these waves is rapidly attenuated, then the waves can be treated essentially as plane waves propagating in a fluid having a shear viscosity coefficient, η. For simple harmonic waves, the shear stress amplitude, T, for waves propagating in the z direction has the form:

$$T = T_o \exp -[\sqrt{\pi\rho f/\eta}\ (1 + j)\ z] \qquad [1]$$

where the simple harmonic time term has been suppressed and where T_o is the initial stress amplitude, f is the frequency, and ρ is the fluid density. In a Newtonian liquid, the shear viscosity coefficient is $\eta = T/\dot{S}$, where S is the shear strain and $\dot{S} = \partial S/\partial t$ is thus the shear velocity. If one assumes that the medium is viscoelastic, η becomes complex and:

$$\eta_c = \eta_1 - j\eta_2 \qquad [2]$$

where η_1 is the real part and η_2 is the imaginary part of the shear viscosity coefficient. For a Newtonian fluid, η_2 is zero. This same phenomenon can also be described by a rigidity modulus, G, which is also complex:

$$G_c = G_1 + jG_2\ , \qquad [3]$$

where G_2 is zero in a perfectly elastic solid and G_1 is zero in a Newtonian fluid. Since $\eta_c = T/j\omega S = -j\ G_c/\omega$ for simple harmonic motion, where ω is the angular frequency,

$$G_1 = \omega\eta_2, \text{ and } G_2 = \omega\eta_1. \qquad [4]$$

The impedance (Z) presented to the rod surface by the sediment is defined as the ratio of shear stress to shear particle velocity in an infinite medium as:

$$Z = R + jX = \sqrt{\pi f\eta\rho}\ (1 + j), \qquad [5]$$

where R and X are the specific acoustic resistance and reactance of the sediment, respectively. Substituting η_c for η in the equations relating η and G and separating real and imaginary parts yields:

$$\eta_1 = \frac{2RX}{\omega\rho} \quad , \qquad \eta_2 = \frac{R_2 - X^2}{\omega\rho} \quad , \qquad [6]$$

$$G_1 = \frac{R^2 - X^2}{\rho} \quad , \qquad G_2 = \frac{2RX}{\rho} \quad . \qquad [7]$$

Thus, shear moduli or viscosities can be calculated by measuring R and X.

Mason (1947) has shown that R and X are related to the change in resonant frequency, Δf, and the change in electrical resistance, ΔR_e, of the transducer driving the system by the equations:

$$\Delta R_e = K_1 R_T \quad ,$$

$$\Delta f = K_2 X_T \quad , \qquad [8]$$

where $R_T = R/L$ and $X_T = X/L$, [9]

and L is the length of the rod immersed. Values for K_1 and K_2 are obtained by measuring resonant frequency and electrical resistance with the rod in air, unloaded, and then loaded by immersion in one of several Newtonian liquids of known viscosity. The observations of ΔR and Δf for this case permits calculation of R and X, since $\eta_2 = 0$ and $R = X$ for the Newtonian fluid. When K_1 and K_2 are known, measuring R and X in the sediment is reduced to measuring ΔR_e and Δf alone.

E. DESCRIPTION OF THE VISCOELASTOMETERS AND PROCEDURES

The viscoelastometer used in previous work consists of a cylindrical torsional oscillator, one-half inch in diameter and about ten inches long. The ends are tapered to permit easier penetration of the sediment. Torsional oscillations are generated by a piezoelectric transducer about 1.5 inches long located at the center and clamped between two lengths of a constant modulus alloy rod. The oscillator is supported at the center by a resilient clamp which also serves to support the electrical leads. The center location of the transducer provides good electromechanical coupling to the first five torsional resonant modes. The fundamental mode frequency is about 5 kHz. The overtones are approximately odd-integer multiples of the fundamental. This oscillator is intended to be completely submerged in the sediment or calibrating fluid.

A new, improved model of the viscoelastometer has been built and is currently being tested. It differs from the one described above by having the driving transducer completely enclosed in the hollow center section of the rod. It is a little thicker, about 0.7 inches, and a bit shorter, about eight inches. Rather than using threaded joints, all joints are made by either press-fitting or a very rigid epoxy resin. The support is a very thin metal thread at one end. The fundamental torsional resonance occurs at about 8 kHz. The advantages for this model are: the sediment is disturbed somewhat less upon insertion due to thin leads protruding from the center, rather than the clamping device. There is a reduced coupling between the torsional oscillations and undesired flexural vibrations in this design due to the increased ratio of thickness to length.

A second, new viscoelastometer has been designed and its construction is nearly complete. Its operation depends upon measuring directly the mechanical impedance of a short, vaned probe imbedded in the sediment when the probe is made to oscillate in torsion. This mechanical impedance will be sensitive to the radiation impedance for shear waves which propagate into the sediment. The torsional oscillations, generated near one end of the system, the top, are coupled to the vaned probe by means of a hollow metal rod of length about 0.8 m. The designed operating frequency is about 1 kHz. The mechanical impedance presented to the vaned head (bottom) due to its twisting motion is determined electrically using appropriate instruments which meter the outputs of the torque and angular velocity sensors located at the head. An expected advantage for this method is that the calibration will be relatively insensitive to temperature. It should be more suitable for in situ measurements.

The relationship between the viscoelastic parameters of the sediment, the dimensions of the vaned probe and the electrical outputs from the torque and the angular velocity sensors are not simple to calculate. A theoretical analysis which will determine this relationship has been started. It attempts to follow and extend the work of Ghosh (1968) who developed solutions for the waves generated in an infinite viscoelastic solid of the Voigt type when the surface of a spherical cavity is given a transient twist.

The calibration of the resonance type of torsional viscoelastometer is carried out using a number of Newtonian fluids of known viscosity and density. As described in Section D, there is a relatively simple relationship between the changes in the resonance frequency of the torsional oscillator and in the electrical conductance at resonance and the viscous parameters of the fluid. The reference condition from which these changes are measured is the complete absence of fluid contact with the wall of the rod. This is achieved by placing the system in a vacuum chamber. It has been found that the surface films which form on the rod when it is exposed to air have an influence on the damping of the oscillations. Temperature must be controlled, since the resonance frequency of the viscoelastometer is somewhat dependent upon temperature. in spite of the use of a constant modulus alloy for parts of its structure.

Once the calibration coefficients are determined, the formulas listed in Section D may be used to determine the real and imaginary parts of the complex shear modulus of a viscoelastic medium when the resonance frequency and the electrical conductance at resonance are measured while the viscoelastometer is inserted in the medium. Insertion of the rod into a sediment causes some disturbance. Efforts made to reduce this include the removal of a core of the sediment only slightly smaller than the rod and allowing time for the sediment to resettle after the insertion. Measurements are conducted at the same temperature at which the calibrations have been made.

F. LABORATORY AND FIELD MEASUREMENTS

We are conducting studies in three types of media: (a) a 4-ft x 8-ft x 3-ft steel tank containing de-gassed, fresh water-saturated kaolinite clay;

(b) a mud tide flat in Elkhorn Slough near the community of Moss Landing, California; and (c) core, grab, and dredge samples of recent marine sediments from Monterey Bay and the Monterey Submarine Fan. Our acoustic measurements include interface (surface) wave speed, compressional wave speed and absorption, and dynamic rigidity as measured with the viscoelastometer. Some mass-physical properties of the sediments are determined to define the sediment type and to seek empirical relationships between static and dynamic test parameters.

1. INTERFACE WAVE MEASUREMENTS

Recognizing the difficulties of making direct measurements of shear wave speed in very soft marine sediments at acoustic frequencies, we are calculating shear wave speed from measurements of the interface wave speed by using relationships developed by Strict and Ginzbarg (1956) and Hamilton, et al. (1969). In our laboratory mud tank, interface waves are generated using a small electrodynamic vibrator and are recorded from vertically-polarized geophones set on the surface of the mud at various distances from the source (Walsh, 1971). Observations are made at interface wave frequencies from 75 to 300 Hz. In the tide flat muds, interface waves are generated by the detonation of a blasting cap at the water-sediment interface and are recorded using the same geophones as for the laboratory mud tank experiments (Lasswell, 1970). These measurements are made at interface wave frequencies of about 100 Hz.

In these two media, the interface wave speed ranged between 20.8 and 28.8 m/sec, giving calculated shear wave speeds of from 21.9 to 33.3 m/sec.

2. COMPRESSIONAL WAVE MEASUREMENTS

Compressional wave speed measurements are made following two techniques: (a) sediment sound velocimeter, using the time delay for the propagation of a short sound burst (with a frequency of 2 MHz) through a known length of cored sediment (Bieda, 1970; Lasswell, 1970; Walsh, 1971); and (b) electrostatic transducer used in conjunction with a cylindrical barium titanate hydrophone for longer propagation paths through sediment in the laboratory mud tank (data processing allows measurement of compressional wave speed at the frequencies of 100, 125, and 150 kHz) (Martinek, 1972).

Compressional wave speeds for cores collected on the tide flat (generally silty clay and clayey silt) varied between 1487 and 1520 m/sec, while samples from Monterey Bay and Monterey Submarine Canyon (generally silt, sandy silt, and clayey silt) varied between 1416 and 1533 m/sec. Sound speed for cores from the mud tank (kaolinite clay) ranged from 1458 to 1479 m/sec, while measurements made using technique (b) for stirred-up, more porous clay yielded a sound speed of 1422 m/sec. The mud tank clay shows much variation in acoustic and mass-physical properties depending primarily upon the elapsed time since the mud was last stirred and de-gassed. Just after stirring, the clay has a porosity of 76.7% and is homogeneous, but it becomes compacted with time and vertical gradients in the mud properties become apparent. Poisson's ratio* for all of these sediments is approximately 0.5.

* as calculated from the compressional and shear wave speeds

In addition to compressional wave speed measurements made in the mud tank, sound absorption is also being measured with the transducer-hydrophone system at the frequencies noted above. For this material with a porosity of 76.7%, the relationship between the absorption coefficient, a, and frequency, f, in kilohertz, is found to be:

$$a = 3.3 \times 10^{-2} f \text{ decibels per meter}$$

which compares favorably with data reported by others for clayey silts (Hamilton, 1972).

3. VISOCOELASTOMETER MEASUREMENTS

The viscoelastometer is used to determine the real and imaginary parts of the dynamic rigidity (complex shear modulus) for the various sediment samples. Core samples are analyzed at various resonant frequencies for the torsional transducer system, primarily at 27 and 38 kHz. Because the viscoelastometer is temperature sensitive, it is calibrated at temperatures near those found at the ocean bottom. Measurement of the dynamic rigidity of the core samples, which are kept at near-in situ temperature prior to testing, is made in a constant-temperature bath to prevent any variations in the calibration values. For samples from Monterey Bay and Monterey Submarine Canyon, the real components of dynamic rigidity (G_1) range from 6.5×10^5 to 2.6×10^7 dyne/cm^2. The imaginary components (G_2) range between 2.9×10^5 and 8.2×10^6 dyne/cm^2. Corresponding shear wave speeds calculated from these data are between 7 and 40 m/sec. For the Elkhorn Slough sediment samples, G_1 ranged between 5.1×10^6 and 2.7×10^7 dyne/cm^2 and G_2 ranged from 1.1×10^6 to 7.9×10^6 dyne/cm^2. Although we have not yet successfuly made measurements of the dynamic rigidity of the kaolinite clay in the laboratory mud tank, calculations show that at a frequency of 15.6 kHz, G_1 should be approximately 3.5×10^5 dyne/cm^2 and G_2 should be approximately 3.6×10^7 dyne/cm^2. These values are comparable to observations reported by Cohen (1968) for a very porous kaolinite mixture.

For the Elkhorn Slough sediments, Lasswell (1970) calculated an average shear wave speed of 29.0 m/sec from measurements of dynamic rigidity with the viscoelastometer and 33.3 m/sec from interface wave speed measurements, showing fairly good agreement between the two methods. With further studies, we hope to show a measured relationship between compressional wave absorption and G_2.

4. MASS-PHYSICAL PROPERTIES

In addition to the acoustic measurements, the following mass-physical properties of the sediment samples are being determined:

a. Vane shear strength, using a motorized Wykeham-Farrance vane shear machine with a Diversified Marine Corporation Adapter Kit to graphically display the relationship between vane torque and degree of rotation;

b. Textural analyses, using the sieve-pipette method and X-ray diffraction quantitative analysis for clay mineralogy;

c. Wet density and porosity, using a known volume of wet, and then dried sediment;

d. Carbon/carbonate content, using the LECO Carbon Analyser.

Our work shows relationships between G_1 and density, porosity, clay content and mineralogy, and vane shear strength. The imaginary component of rigidity, G_2, shows some dependence on clay content and mineralogy, inferring that G_2 is dependent on a factor related to clay type and amount or the structure of the clay deposit. Our results to date point out the importance of making in situ measurements of dynamic rigidity to avoid as much as possible the disturbance of the sediment. Recent discussions with personnel from the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California, have indicated to us the importance of measuring the Atterberg limits of our sediment samples, leading to usage of the Unified Soil Classification System for communication between acousticians and soil engineers.

5. CONCLUSIONS AND FUTURE WORK

Based on the preliminary measurements of the dynamic shear properties of sediments reported here, the viscoelastometer method yields results which compare quite favorably with these properties as reported by others using independent methods.

We plan to refine the laboratory measurements by conducting simultaneous measurements of compressional and interface wave propagation and of dynamic rigidity. Recognizing the problems of disturbance due to sampling of natural sediments and of the artificiality of the laboratory in situ experiments, preparations are under way for simultaneous in situ shallow water field experiments using various methods. The planned site for these tests is in Elkhorn Slough near Moss Landing, California.

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TASK 2 - THE STUDY OF UPPER OCEAN TURBULENCE AS RELATED TO ACOUSTIC MEASUREMENTS

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B. INTRODUCTION

This report is a summary of research carried out during FY 72. The object of the research completed on this project during the past fiscal year was to gain some understanding of the interrelations between water surface displacement, wave particle velocity, temperature fluctuations, salinity fluctuations, and their effects on sound amplitude and phase modulations. Effort during FY 72 was concentrated on field studies at the NURDC Oceanographic Tower off San Diego, California. Experiments were carried out in October 1971 and June 1972. Some analyses have been completed and further analyses of the data are in progress.

The NURDC tower is located in approximately 16 meters of water one mile off Mission Beach in San Diego. The tower has rails on three sides and mounted carts which can traverse vertically from the tower platform to the bottom. The instrumentation to measure the various parameters was mounted on the most seaward (westward) cart and measurements were made at various elevations.

The objective of the two experiments was to completely describe the small-scale physical properties in the upper ocean in order to determine their temporal and spatial interrelationships.

The parameters measured in the October experiment included orthogonal water particle velocities (turbulence), an array of four temperatures, salinity, sound speed, sound speed (phase) modulations and sound amplitude modulation in one direction (westward), and the surface waves measured close to the point of interest. Simultaneous time series measurements for prescribed lengths of time were made. A concurrent experiment was conducted in order to infer the size and number of bubbles in the water by accurate measurement of the speed of sound as a function of frequency.

The same parameters were measured in the June 1972 experiment but additional sensors were used and their location with respect to the tower and to each other was changed to improve the experiment. The frame carrying the sensors was offset six feet from the cart which allowed sensors to be placed further from the influence of the tower. Sound was propagated and received in three orthogonal directions. In addition, two matched hydrophones were placed in line in the horizontal (westward) direction in order to measure sound phase variations as a function of frequency. A Baylor wave gauge was mounted directly above the two-component flow meter which was attached to the bottom of the frame. A second Baylor gauge (operated by NURDC) was several meters south of the frame-connected Baylor gauge. The array of four thermistors was placed horizontally along the southern bottom frame member. No pressure sensitive wave detector was used during this experiment.

C. REVIEW OF INSTRUMENTATION

1. OCTOBER 1971

The turbulence measurements were made using an electromagnetic flow meter manufactured by Engineering Physics Company. This instrument is capable of measuring two-orthogonal components simultaneously. The resolution of this instrument is limited by the wave number scale because of the volume over which the flow velocity is integrated. This limits this particular model to measurement of turbulence with wave lengths greater than about 20 centimeters. Using Taylor's hypothesis, this limits the frequency resolution to about one Hertz.

Temperature measurements were made using thermistors having a time constant of 0.2 seconds. Several temperature sensors were used simultaneously in an attempt to obtain spatial correlation of temperature. A Bissett-Berman salinometer was used to obtain temporal variation of salinity. The speed of sound was taken using a Ramsey SVTD probe. The amplitude and phase modulation of a continuous sound wave of 60 kHz were measured using a source and hydrophones separated by approximately two meters. The surface waves were measured using a surface penetrating resistance wave gauge manufactured by Baylor Company and a pressure wave sensor made by Interstate Electronics. In all, eleven simultaneous measurements were attempted in the first experiment. All data were recorded on a 14 channel Sangamo model 6500 tape recorder using FM electronics.

2. JUNE 1972

This experiment was similar to the October experiment but with improvements in the arrangement and number of sensors used. The sound amplitude and phase modulations were measured over three orthogonal paths at frequencies 60 and 105 kHz. Four hydrophones were used, two of these spaced one meter apart on the westward sound axis. The Baylor wave gauges have already been discussed.

Two smaller versions of the electromagnetic flow meter were ordered under this contract and were planned for use in the June experiment. These instruments, with higher frequency resolution, did not arrive until two weeks after completion of the experiment. As a result the same instrument as in the October experiment was used. The Bissett-Berman salinometer (and temperature) and the Ramsey SVTD probe were again used.

Two tape recorders were used to record all the signals. In addition to the Sangamo recorder used in September 1971, a 7-channel Precision Instrument tape recorder was also used to accommodate all the signals. A common signal from an oscillator was recorded on both tape recorders for synchronization of signals. In June, FM electronics were not used exclusively. For greater accuracy, the FM signals from the Ramsey probe and Bissett-Berman salinometer were recorded on direct electronics. Time varying voltage signals will be recovered by playing these recorded frequencies into the deck units of the two instruments. Whenever possible output signals were monitored on an oscilloscope or recorded on strip charts.

The June experiment took place during 4 - 9 June. Sound measurements requiring minimum sound scatter were made during the evening of 4 June and the day and evening of 5 June; the third day was used for completing the rigging of the frame with the bulk of the main equipment. The last two days were used for combined sound and oceanography measurements.

D. DATA ANALYSIS

The statistical and spectral descriptions of the various parameters are being determined. The relative frequency distributions are being determined and theoretical probability and joint probability distributions sought. Correlation and cross-correlation functions and spectral quantities are being calculated in an effort to determine interrelations of the measured quantities. Spectral quantities being calculated are the spectra, cross-spectra, phase and coherence of the various measured parameters.

The amplitude and phase of the continuous sound wave are changed if fluctuating inhomogenities exist in temperature, salinity, water particle velocity or bubbles. The sound is scattered only slightly by particles in the water but bubbles can act as particularly good scatterers. The effects of all these variables act on the sound wave over the path from source to the receiver. The amplitude and phase modulation are then measurers of the integrated effects of the environment over a certain path length. It is expected that these effects are a function of propagation direction and the three orthogonal sound paths are designed to study this anisotropy.

Simultaneous with the sound amplitude and phase modulations, the temperature, salinity, and water particle velocities are measured at points adjacent to the sound path in order to determine the environment at the various points. For instance, the wave number spectrum for temperature can be obtained by measuring the instantaneous temperature at a number of points over the path. In this manner it is hoped to go beyond the theories of Chernov and Tatarski and to determine the cause of the sound amplitude and phase modulation signals at sea. The size of inhomogeneties of the physical properties can be inferred from measurements at varying sound frequencies. In this manner pertinent length scales can be determined, thus furnishing an acoustic tool for measuring oceanographic variables.

The primary effort of the October 1971 experiment was to determine temporal descriptions and interrelations. In the June experiments the wave number spectra were measured in an effort to determine the spatial variations and length scales. The frequency range considered was from DC to 2 Hz. This is the band of principal spectral-density of the measured quantities. An effort to extend this range with improved instrumentation was made in June 1972.

E. WORK COMPLETED

Two theses based on work performed at the NURDC tower in October were completed in December 1971. Three more theses based on October 1971 data were completed in March 1972. These theses have previously been sent to ONR. The abstracts of these five theses are attached for reference convenience.

F. WORK IN PROGRESS

LCDR Fitzgerald and LT Alexander are working on the sound amplitude phase and decorrelation data. Their work is expected to be completed in October 1972.

LCDR Gossner is examining correlations between sound speed variations and variations in other oceanographic parameters such as salinity and temperature. He will compare measured sound speed results with values calculated from common sound speed equations and check their validity for shallow water application.

LT Frigge will carry out detailed examination of the Bissett-Berman STD. In addition to the NURDC experiment, additional measurements will be made to check its response under various flow conditions. This work is in response to findings made during the October 1971 experiment.

LT Whittemore will continue to examine scales of temperature variations occurring in shallow water. Additional data probably will be required.

LT Haley is investigating the interrelationship of the various measured parameters to determine physical relationships. He is analyzing the records obtained in the October experiments for the cross spectral quantities of coherence and phase. Appropriate band pass filters are being investigated to enhance the signal comparisons. Ultimately, transfer functions are being sought between the various parameters.

LT Krapohl is comparing the measured water particle spectra with the theoretical spectral values calculated from the water surface measurements. Directional spectra will be determined from the flow meter measurements and these will be used to relate the temporal fluctuations and spatial variations measured in the other quantities.

LT Haley's thesis is expected to be completed in December 1972. The studies of Gossner, Frigge, Whittemore, and Krapohl are expected to be completed in March 1973.

G. APPENDIX - MASTERS THESES COMPLETED UNDER THIS PROJECT

AMPLITUDE MODULATION OF AN ACOUSTIC WAVE PROPAGATING NEAR THE OCEAN SURFACE

BY

W. J. Smith, Jr.

ABSTRACT

Sixty KHz CW sound was propagated parallel to and near the ocean surface adjacent to an array of four thermistors, a salinometer, a sound velocimeter, a turbulent velocity probe, and a wave-height probe in order to investigate the statistics and environmental causes of amplitude modulation. The temporal variations of the sound amplitude were studied during four twenty-minute runs over a range of two meters at varying depths from near the surface to 14 meters during sea-state one conditions in water of 16 meters depth. Analysis indicated mean percentage amplitude modulation of approximately 5 percent with a variance of approximately 10^{-3}. Temporal correlation times were about two seconds except for a seven second time near the bottom. The power spectral densities of the modulation show strong components corresponding to predominant ocean wave frequencies as well as higher frequencies that may be attributed to bubble, temperature and/or salinity inhomogeneities. There is evidence that the microstructure dimensions are larger near the bottom than in the upper and middle depths.

SOUND DISPERSION AND PHASE FLUCTUATIONS IN THE UPPER OCEAN

by

Juergen Rautmann

M. S. Thesis, Naval Postgraduate School

ABSTRACT

In situ measurements of the speed of sound in the upper ocean have shown the existence of significant dispersion and large fluctuations in the frequency range 28-80 kHz. The dispersion in the speed of sound shows two peaks centered at the frequencies 30 and 69 kHz presumably caused by resonant bubbles of average radii 124 and 54 microns. The maximum deviation in a from the bubble-free value is 6 m/sec. with a maximum error of .5 m/sec. It is possible to identify bubbles of radius centered around 54 microns at depth 4.3 meters as well as a peak centered around 124 micron radius detectable down to 14.3 m. A statistical analysis of the phase fluctuations shows near Gaussian probability-density functions except at the dispersion center frequencies. The standard deviation of the phase fluctuations ranges from 3.84 degrees at 40.6 kHz to 1.92 degrees for frequencies from 46.4 to 61.8 kHz. The temporal fluctuations of the speed were principally at surface wave orbital frequencies and appear highly correlated with them.

SPECTRAL MEASUREMENTS

of

WATER PARTICLE VELOCITIES UNDER WAVES

by

Michael William Bordy

ABSTRACT

Simultaneous measurements of the instantaneous sea surface elevation and water particle velocities were made using a wave staff and an electromagnetic current meter. Measurements were made at three elevations in 18 meters of water at an open ocean site during moderate wave and wind conditions. Coherence of the wave height and orbital velocities was computed to be greater than 0.90 through the range of significant energy-density between 0.05 and 0.22 Hertz. This range contained greater than 90 percent of the total spectral energy-density which indicated that the water particle velocities were almost totally wave induced. Measured velocity energy-density spectra were compared to theoretically computed spectra using linear wave theory formulation. The measured spectra were 27 to 45 percent greater than theoretical spectra indicating that measured velocities were 5 to 7 percent greater than the theoretical value. Phase spectra were computed for the measured wave heights and orbital velocities. They compared reasonably with first order wave theory.

THE MEASUREMENT AND CORRELATION OF SOUND VELOCITY AND TEMPERATURE FLUCTUATIONS NEAR THE SEA SURFACE

by

Charles Jack Duchock, Jr.

ABSTRACT

The temporal variation of salinity, temperature, water turbulence components, surface wave height, acoustic amplitude and acoustic velocity were studied statistically by computing the auto-correlations and power spectral densities. Correlation times were high for temperature fluctuations with a decay time (e^{-1}) being of the order of forty seconds or greater for temperature and of the order of two seconds for the other parameters. All parameters were shown to exhibit maximum energy at the periods of the predominant surface wave energy.

STATISTICAL RELATIONS
BETWEEN SALINITY, TEMPERATURE
AND SPEED OF SOUND IN THE UPPER OCEAN

by

Harry Augustus Seymour, Jr.

ABSTRACT

In situ measurements of salinity and temperature fluctuations at depths to 14 meters indicate distinct dependencies at different times of the day. The variance of the salinity fluctuations decreased with increasing depth, but was greater just after sunrise than just prior to sunset. The variance of the temperature fluctuations decreased with increasing depth just prior to sunset, but increased with depth immediately after sunrise. The correlation length of the sound index of refraction was calculated by using the variance of the sound velocity fluctuations, and the variance of sound amplitude modulation in the theory of Mintzer. This analysis shows that microstructure patch size increases approximately linearly with depth. The power spectral densities of the salinity, temperature and sound velocity fluctuations show peaks of energy corresponding to dominant ocean wave frequencies.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Study of Dynamic Rigidity of Marine Sediments and Study of Upper Ocean Turbulence as Related to Acoustic Measurements

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*

Annual Progress Report

5. AUTHOR(S) *(First name, middle initial, last name)*

Robert S. Andrews, O. B. Wilson, Jr., Noel E. J. Boston, Herman Medwin, and Edward B. Thornton

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1972	22	19

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. NR 083-275	NPS-58AD72081A
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for Public Release; Distribution Unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Office of Naval Research

13. ABSTRACT

This report covers progress for the period 1 July 1971 through 30 June 1972 under Research Project RR 131-03-01, NR 083-275, Office of Naval Research, Ocean Science and Technology Branch. The report is divided into two tasks with each task summary being prepared by the principal investigators of that task. Task 1 includes a study of the dynamic rigidity, acoustic, and other engineering properties of marine sediments. Task 2 covers a study of upper ocean turbulence as related to acoustic measurements.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Viscoelastic						
Acoustics						
Marine Sediments						
Dynamic Rigidity						
Shear Modulus						
Turbulence						
Ocean Turbulence						
Temperature Fluctuations						
Ocean Waves						